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Nano-texture for a wear-resistant and near-frictionless diamond-like carbon

Ala' A. Al-Azizi [a], Osman Eryilmaz [b], Ali Erdemir [b], Seong H. Kim [a,*]

[a] Department of Chemical Engineering and Materials Research Institute, The Pennsylvania State University, University Park, PA 16802, USA
[b] Energy Systems Division, Argonne National Laboratory, Argonne, IL 60439, USA

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ABSTRACT

The effect of nano-scale surface texture on wear resistance of diamond-like carbon (DLC) films was studied using a reciprocating ball-on-flat tribometer in dry, humid, and liquid water environments. The nano-scale surface texture was produced by depositing ~1 μm thick DLC films onto silicon substrates pre-textured with pyramidal wells and polystyrene spheres. The surface roughness of the textured DLC films was about 50 nm in both cases. The friction and wear behavior of the flat and nano-textured DLC films were tested with AISI 440C-grade stainless steel balls at a contact load creating about 360 nm deep Hertzian deformation which is significantly larger than the surface roughness. At this condition, nano-texturing did not affect the friction coefficient, but it significantly reduced the wear of DLC films in dry and humid nitrogen compared to flat DLC. In dry nitrogen, the nano-textured DLC films showed the ultra-low friction without substantial wear of DLC and deposition of thick transfer films onto the counter-surface. The wear reduction appeared to be related to the stress relief in the nano-textured DLC film. In liquid water, surface features on the nano-textured DLC films were diminished due to tribochemical oxidation and material removal at the sliding interface.

1. Introduction

Diamond-like carbon (DLC) has unique physical, mechanical, and tribological properties which make it a good candidate as a solid lubricant for a variety of industrial applications [1]. In dry environments, DLC gives an ultralow friction coefficient (<0.01) usually preceded by a run-in period with high friction. The wear of DLC takes place mostly during this run-in period, which results in the formation of transfer film on the counter surface. This initial wear of DLC could be prevented through the adsorption of alcohol molecules from the vapor phase; but this is associated with the loss of the ultra-low friction coefficient [2–4].

For lubrication performance of DLC films, surface passivation and transfer film formation are considered two important factors [5–7]. It was found that hydrogen-free DLC film failed to lubricate for prolonged cycles [8], while friction quickly decreased to its ultra-low value when hydrogen gas was introduced to the test environment [9]. Molecular dynamic simulations showed that hydrogen atoms adsorbed on DLC film reduced adhesion and friction by decreasing the number of interacting carbon atoms at the interfaces [10,11]. However, the passivation of DLC surface with other molecules like water vapor or alcohol vapor did not give ultra-low friction [2,3]. The steady-state ultra-low friction of DLC is often observed after the counter-surface is covered

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* *Corresponding author*: Fax: +1 8148657846.
E-mail address: shkim@engr.psu.edu (S.H. Kim).

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with a transfer film [12]. The nature and structure of this film are complicated [4,13–16]. It was suggested that DLC graphitizes during sliding due to relaxation of sp^3 bonds, and thus-formed graphite is responsible for the ultra-low friction observed [13–17]. However, DLC graphitization has been reported regardless of ultra-low friction in dry nitrogen and argon environments or high friction in ambient conditions [13]. Furthermore, graphite does not lubricate in inert environments (like dry nitrogen) or in vacuum, but hydrogenated DLC still shows ultralow friction in these environments [14]. This indicates that graphitization cannot be the sole reason for the ultralow friction of DLC.

In DLC lubrication studies, the effect of surface roughness is often overlooked. The main challenge in understanding the effect of roughness lies in the difficulty to roughen DLC surfaces in a controlled manner. Laser-induced texturing causes structural changes in the DLC film due to the prolonged exposure to intense heat from the laser pulses [18–20]. Therefore, rough or textured DLC surfaces were mainly produced by coating DLC films on roughened substrates. Well-defined micro-scale textured DLC was produced by coating DLC on silicon textured by standard photolithographic techniques [21–23]. In the boundary lubrication regime, micro-scale grooves and trenches act as reservoirs which can constantly replenish the contact area with liquid lubricant if these textures have the correct size and orientation with respect to the sliding direction. In the hydrodynamic lubrication regime, on the other hand, surface texture was found to change the hydrodynamics of the system. Surface texture can provide larger effective clearance between sliding surfaces which increases the load-carrying capacity and reduces friction and wear [24,25]. DLC films with sub-micron roughness were studied by coating DLC on metal substrates pre-roughened by mechanical polishing [26,27] or by sputtering [28]. The chaotic nature of mechanical scratches and the irregular features of these substrates resulted in inhomogeneous DLC films [29]. This often caused chipping and fragmentation during sliding, and more wear of the DLC film or the counter surface [26–28].

In this paper we show that nano-texturing of DLC can achieve ultra-low friction in inert environment without the formation of substantially thick transfer film onto the counter surface. Nano-textured DLC was created by depositing thick DLC films on silicon substrates textured with nano-wells or nanoparticles. Nano-textured DLC exhibited significantly shorter run-in period with very little transfer film compared to flat DLC. Furthermore, DLC wear, and transfer film obtained from the nano-textured DLC were compared to those obtained from flat DLC in the presence of adsorbed water and in liquid water. Possible mechanisms on the nano-texturing effects on friction and wear of DLC were discussed.

2. Experimental techniques

Textured DLC samples were produced by coating DLC films on silicon substrates pre-textured with nano-wells and polystyrene colloidal particles. Silicon (100) substrates were chemically etched via maskless etching process using 1 μm-diameter positively charged amidine-functionalized polystyrene latex colloids (APSL). More details about the etching procedure can be found in the previous publications [30,31]. Two types of nano-textures were produced; nano-wells, which were the inverted pyramids (Fig. 1a) etched in the silicon substrate, and nano-domes, which were the same pyramids in Fig. 1a with the APSL colloids inside them (Fig. 1c). One micron-thick, highly-hydrogenated DLC films were then coated on the flat and the textured silicon substrates using a plasma enhanced chemical vapor deposition process following the procedure described in the previous publication [32]. Fig. 1b and 1d show scanning electron microscopy images (taken with FEI Quanta 200 Environmental SEM) of the DLC-coated textured silicon substrates. Hereafter, the DLC films deposited on flat silicon substrate, silicon substrate with nano-wells, and silicon substrate with nano-domes will be called flat DLC, DLC-on-wells, and DLC-on-domes, respectively.

Fig. 2a–c show the SEM cross section images (taken with FEI NanoSEM 630 FESEM) of flat DLC, DLC-on-wells, and DLC-on-domes, and Fig. 2d–f show optical profilometry images of the three surfaces taken with Zygo NewView 7300 instrument. From the cross section images, the average DLC film thickness was found to be 1.3 μm. From optical profilometry, flat DLC was found to have ~3 nm RMS roughness. Both DLC-on-wells and DLC-on-domes had an RMS roughness of 50 nm. The average feature height was ~120 nm on both DLC-on-wells and DLC-on-domes. The skewness and kurtosis of the DLC-on-domes were 0.43 and 2, respectively. The positive skewness and the kurtosis value lower than three indicated that the topography of the DLC-on-domes was more like upward protrusions. On the other hand, DLC-on-wells had less positive skewness (0.19) compared to the DLC-on-domes, and had a kurtosis of 3. These values suggested that the DLC-on-wells had more symmetrical topography around the mean plane compared to the DLC-on-domes.

A home-built reciprocating ball-on-flat tribometer was used to perform the friction and wear tests [33]. Commercially available 440C stainless steel balls with a diameter of 3 mm

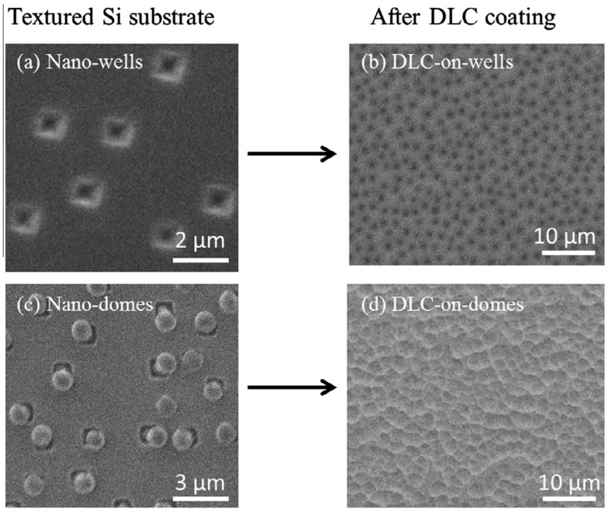

Fig. 1 – (a) 1 μm nano-wells etched on silicon substrate. (b) DLC-coated nano-well substrate. (c) Nano-domes (polystyrene sphere inside nano-wells) on silicon substrate. (d) DLC-coated nano-dome substrate.